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James T. Webb, Ph.D., and Andrew A. Pilmanis, Ph.D.

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7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)
Wyle Laboratories, Life Sciences, Systems and Services Inc.
2485 Gillingham Drive
San Antonio, TX 78235-5105

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9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)
High Altitude Protection Research
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14. ABSTRACT
A 10.2 psi staged-decompression schedule ("camp-out procedure") or a 4-hour preoxygenation at 14.7 psi is required prior to extravehicular activity (EVA) to reduce decompression sickness (DCS) risk. Results of recent research at the Armstrong Laboratory showed that a 1-hour resting preoxygenation followed by a 4-hour, 4.3 psi exposure resulted in 77% DCS risk (N=26), while the same profile beginning with 10 min of exercise at 75% of VO2peak during preoxygenation reduced the DCS risk to 42% (P<.03; N=26). A 4-hour preoxygenation without exercise followed by the 4.3 psi exposure resulted in 46% DCS risk (N=28; preliminary). The 1-hour preoxygenation with exercise and the 4-hour preoxygenation without exercise results were not significantly different. Elimination of either 3 hours of preoxygenation or 12 hours of staged-decompression are compelling reasons to consider incorporation of exercise-enhanced preoxygenation.

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A NEW PREOXYGENATION PROCEDURE FOR EXTRAVEHICULAR ACTIVITY (EVA)

James T. Webb, Ph.D.[1] and Andrew A. Pilmanis, Ph.D.[2]

[1] KRUG Life Sciences Inc.
AFRL/HEPR
2504 Gillingham Drive, Suite 25
Brooks AFB, TX 78235-5104

[2] High Altitude Protection Laboratory
AFRL/HEPR
2504 Gillingham Drive, Suite 25
Brooks AFB, TX 78235-5104

ABSTRACT

A 10.2 psi staged-decompression schedule or a 4-hour preoxygenation at 14.7 psi is required prior to extravehicular activity (EVA) to reduce decompression sickness (DCS) risk. Results of recent research at the Air Force Research Laboratory (AFRL) showed that a 1-hour resting preoxygenation followed by a 4-hour, 4.3 psi exposure resulted in 77% DCS risk (N=26), while the same profile beginning with 10 min of exercise at 75% of VO_{2peak} during preoxygenation reduced the DCS risk to 42% ($P<.03$; N=26). A 4-hour preoxygenation without exercise followed by the 4.3 psi exposure resulted in 47% DCS risk (N=30). The 1-hour preoxygenation with exercise and the 4-hour preoxygenation without exercise results were not significantly different. Elimination of either 3 hours of preoxygenation or 12 hours of staged-decompression are compelling reasons to consider incorporation of exercise-enhanced preoxygenation.

1. INTRODUCTION

1.1 Cause and Prevention of Decompression Sickness (DCS)

Tissues and fluids of the body are saturated with nitrogen at the partial pressure of nitrogen in the atmosphere. In the Space Shuttle, Mir, and the atmosphere planned for the completed International Space Station (ISS), the partial pressure is about 80% of the 760 mm Hg total pressure. The 600 mm Hg N_2 partial pressure is approximately equal to sea level N_2 partial pressure. During decompression, total atmospheric pressure is reduced faster than the partial pressure of nitrogen is reduced in the tissues, yielding a supersaturation. A supersaturation provides the potential for gas bubble formation and growth. DCS symptoms result from effects of gas bubbles on tissues and fluids of the body.

Protection from DCS is obtained by denitrogenation, i.e., getting rid of nitrogen. Inspiring less nitrogen allows denitrogenation to occur. Therefore, the partial pressure of nitrogen in the breathing mixture is a critical factor which influences efficiency of denitrogenation. A low partial pressure of nitrogen in the breathing mixture creates a gradient for diffusion of nitrogen out of the

tissues, into the blood, and out of the body via the lungs. Breathing 78% nitrogen at sea level accomplishes no denitrogenation because it creates no gradient. A breathing gas of 100% oxygen is ideal and better than a mixture of 90% oxygen and 10% nitrogen [1]. Preoxygenation, or prebreathing, is breathing 100% oxygen before decompression, and is a very effective form of denitrogenation. The longer preoxygenation lasts, the more nitrogen is removed by diffusion and perfusion [8].

Tissue perfusion directly controls rate of denitrogenation and is affected by a number of factors including, on earth, gravity and body position [3]. Pooling of blood at 1G slows perfusion and denitrogenation. A supine body position allows better return of blood to the heart in 1G conditions. Weightlessness minimizes the type of blood pooling which slows denitrogenation.

Exercise increases ventilation and tissue perfusion. By increasing perfusion, exercise allows more nitrogen to diffuse into blood returning to the heart per unit of time and increases efficiency of denitrogenation. The additional heat produced by exercise causes peripheral vasodilation which enhances denitrogenation of skin tissue. Earlier efforts showed increased protection from DCS by performing exercise during preoxygenation [1, 6, 9]. Neither the USAF nor NASA currently use exercise to enhance preoxygenation.

1.2 Current NASA EVA Denitrogenation

Currently, to reduce DCS risk, all NASA Space Shuttle crewmembers undergo a 10.2 psi staged-decompression schedule with EVA crewmembers accomplishing two 100% oxygen preoxygenation periods for a total of about 14 h (Fig. 1). The reduced partial pressure of nitrogen respired during the staged decompression, about 388 vs 600 mm Hg partial pressure of nitrogen, allows a slow denitrogenation to occur while crewmembers accomplish normal duties. Waligora et al. [7] showed that the staged-decompression procedure was as efficient at preventing DCS symptoms as an alternative denitrogenation consisting of a 4-hour preoxygenation at 14.7 psi.

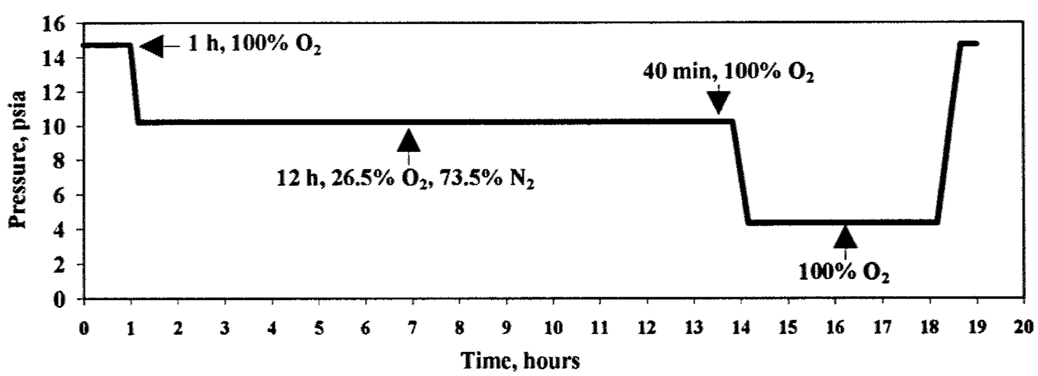

Figure 1. Current NASA EVA Denitrogenation Profile

Since that time, we have tested the use of exercise during preoxygenation as a means to shorten the time required to achieve adequate denitrogenation [10]. The research described below includes results from a completed protocol [10] and an ongoing protocol at the Air Force Research Laboratory, Brooks AFB, TX.

2. METHODS

2.1 Subjects

The voluntary, fully-informed consent of the subjects used in this research was obtained in accordance with AFI 40-402. All subjects passed an appropriate subject physical, and were otherwise representative of the USAF rated aircrew population. They were not allowed to participate in SCUBA diving, hyperbaric exposures, or flying for at least 72 h before each scheduled altitude exposure.

2.2 Exposure Parameters

Table I summarizes preoxygenation conditions for the tests. The exercise during preoxygenation was as described in Webb et al. [10], using a dual-cycle ergometer (Fig. 1).

Prior to each altitude exposure, a medical monitor conducted a short physical examination of subjects to identify any signs of illness or other problem which would endanger the subject or bias the experimental results. A neck-seal respirator made by Intertechnique® (Plaisir Cedex, France) was used for oxygen delivery and is shown in Fig. 1. It provided a slight, 2 cm of water, positive pressure which reduced the opportunity for inboard leaks of nitrogen from ambient air. The respirator was used for preoxygenation, ascent, altitude exposure, and descent. It delivered 100% oxygen (aviator's breathing oxygen; normal analysis 99.7-99.8% oxygen). Three full inspiration/expiration cycles were completed after donning the mask to reduce the nitrogen concentration in the mask and in the conducting airways.

After each of the 3 preoxygenation profiles, the subjects were decompressed at 5,000 ft/min to 4.37 psia (30,000 ft, 226 mm Hg; 9,144 m; nnn kPa). The planned exposure was 4 h during which subjects performed mild exercises [10] designed to be identical with those of Waligora et al. [7, 8].

Table I. Preoxygenation Conditions

Short description[1]	Total preoxygenation, min	Exercising preoxygenation, min	Supine, resting preoxygenation, min	Subject n
10E+50R[2]	60	10	50	26
240R[3]	240	0	240	30
15E+75R[4]	90	15	75	30

[1] E = exercise, dual-cycle ergometry (two Ergomedic 818Es from Monark® operated upright in tandem or one Ergomedic 818E and one 881E arm ergometer from Monark®, Varberg, Sweden as shown below) at 75% of peak oxygen uptake performed at the beginning of preoxygenation (Webb et al., 1996); R = supine rest

[2] from Webb et al. (1996)

[3] Designed after Waligora et al. (1984)

[4] Designed after Webb et al. (1996)

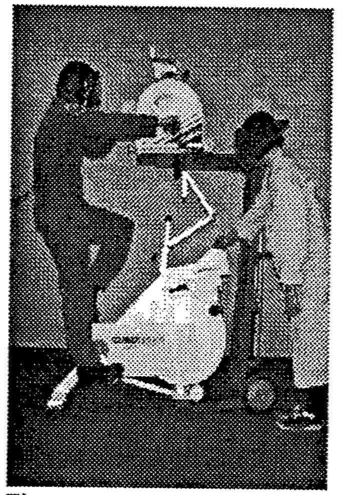

Figure 2. Dual-cycle ergometer

2.3 Data Collection

An HP SONOS 1000 Echo-Imaging System was used to detect and record information about precordial circulating gas bubbles observed during each exposure [10]. Endpoints of the exposures were: 1) completion of 4-h at 4.37 psia (30,000 ft, 9,144 m); 2) development of DCS signs or symptoms such as neurological, peripheral, or respiratory; or 3) development of Grade 2 DCS joint pain. DCS joint pain was graded as follows: Grade 1) intermittent, mild to moderate pain, intermittent or constant joint awareness or "fullness"; Grade 2) constant, tolerable, mild to moderate pain [11]. Subjects were not questioned about how they felt during the altitude exposures. However, they did receive a briefing on the morning of each exposure which emphasized their responsibility to report any DCS symptoms to chamber personnel. Only DCS endpoint symptoms meeting this definition are reported here.

3. RESULTS AND DISCUSSION

3.1 Observations

The 4-hour resting preoxygenation resulted in 47% DCS (N=30). The 1-hour preoxygenation with a 10-min exercise resulted in 42% DCS (N=26) [10]. The 1.5-h preoxygenation with a 15-min exercise resulted in 53% DCS (N=30). A Chi Square test showed no difference in DCS incidence between these three exposures (Fig. 3). This implies there is no advantage to increasing the duration of exercise, despite increased preoxygenation duration. All cases of DCS which occurred during these tests reolved during descent to ground level pressure and no delayed or recurring symptoms were observed.

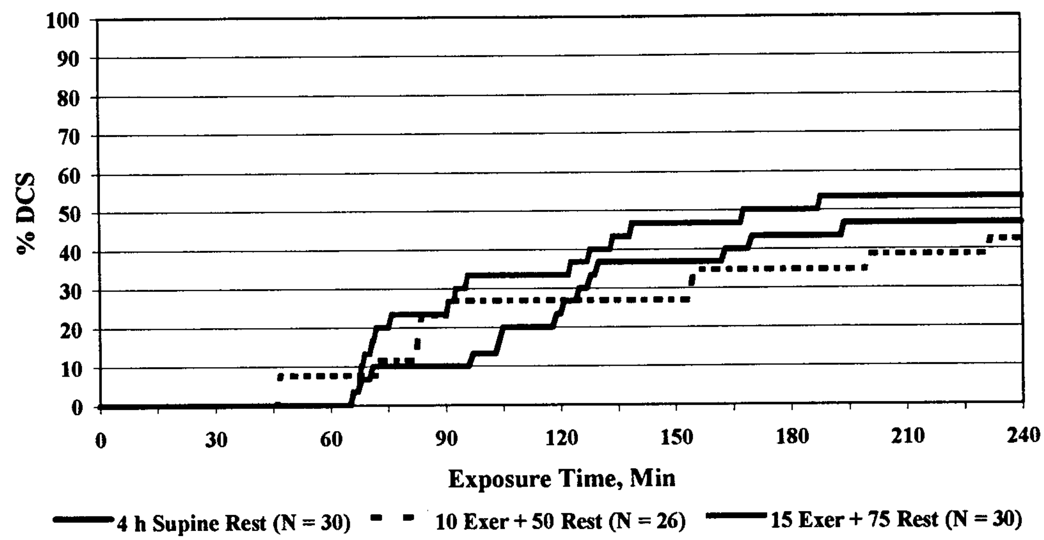

Figure 3. Cumulative DCS Incidence during Exposure to 4.3 psia as a Function of Preoxygenation Condition: Air Force Research Laboratory Results

The time spent denitrogenating prior to EVA is shown in Figure 4. The savings of time by enhancing preoxygenation with exercise represents a potential for increased efficiency without increasing fatigue. Indeed, the exercise suggested may substitution for a portion of that day's scheduled exercise to reduce deconditioning due to weightlessness.

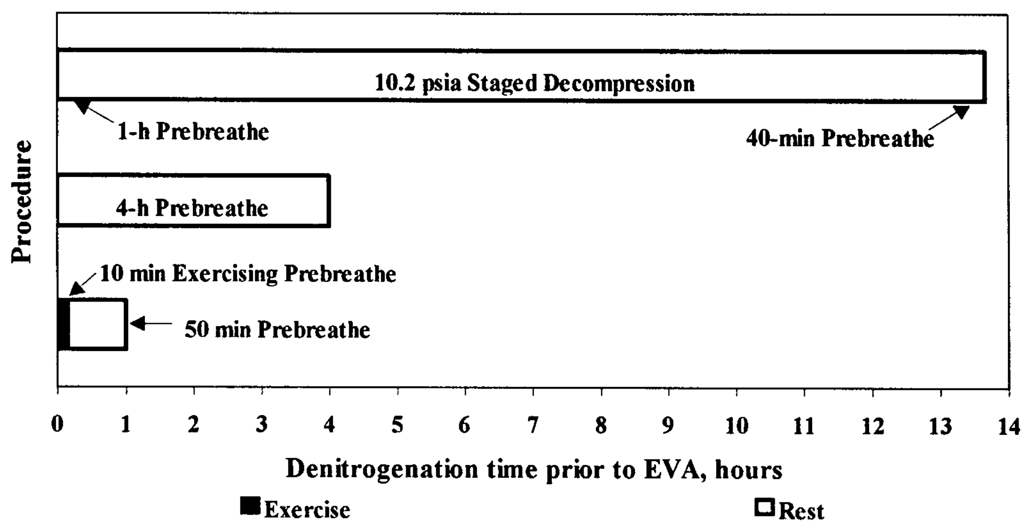

Figure 4. Denitrogenation Options prior to EVA

3.1 Comparison with NASA Results

While our findings indicate 47% DCS risk following a 4-h preoxygenation, results from NASA JSC indicate only 21% DCS risk after the same period of resting preoxygenation despite using the same exposure parameters (Fig. 4). Differences, although not statistical, between Air Force Research Laboratory and NASA results, may be due to a subtle difference in DCS joint pain grading and interpretation of DCS as an endpoint in the experiment. The Air Force Research Laboratory Grade 2 joint pain category may include several of the symptoms described as Grade 1 during the NASA study. Adjustment for this difference would have the effect of removing most of the variation in results between the two labs. In any case, comparison of a 4-h resting preoxygenation and a 1-h exercise-enhanced preoxygenation, both accomplished at the same lab under identical grading criteria as well as identical exposure conditions, should allow an adequate appraisal of difference in risk level followng the two denitrogenation procedures. That comparison showed no difference.

Comparison of our results following a 4-h preoxygenation with operational reports during EVA, with zero reported incidence of DCS symptoms, also requires explanation. Ground-based DCS studies have typically involved ambulatory subjects. On-orbit, the crewmembers preparing for, and accomplishing EVA, are weightless. Weightlessness removes the weight of the upper body on foot, knee and hip joints. Removal of lower joint stress can be termed adynamia. Adynamia has the effect of reducing potential for gas bubble formation due to sheer stresses in lower body joint tissue as weight is applied during dynamic movement such as walking. One way of controlling for the effect of adynamia on incidence of DCS during ground-level studies is to keep the subjects reclined (supine) during both preoxygenation and exposure [4].

3.2 Reporting and Other Differences Between Laboratory and Operational Results

Another difference between reporting of DCS during ground-level studies and EVA, with all its distractions and a dedicated mission-oriented attitude, is dependence on a DCS symptom being significant enough to be noticed or considered worth reporting. It is possible that about half of the symptoms noted during our studies would not even be noticed by a crewmember during EVA. Also, our subjects are encouraged to report symptoms, without any penalty; whereas, at a minimum, a report of DCS during EVA would jeopardize completion of the EVA mission and possibly the future of that crewmember in an EVA role. In our studies, by using the same endpoint, the same criteria for DCS joint pain grading, and by briefing all subjects to report symptoms without hesitation or consequence, effects of these variables are minimized.

4. CONCLUSION

The 1-hour preoxygenation beginning with 10 min of exercise at 75% of peak oxygen uptake produced the same level of DCS observed during identical exposures following a 4-hour resting preoxygenation. Increasing the exercise duration did not increase protection from DCS. Adynamia and increased preoxygenation duration may reduce DCS incidence in ground-based studies, yielding results more in line with the current level of operational risk, that is, zero.

Allowing EVA from a 14.7 psia environment within 90 min of beginning preoxygenation or elimination of a 14-hour staged decompression procedure are compelling reasons to consider incorporation of exercise-enhanced preoxygenation. This alternative to the current procedures,

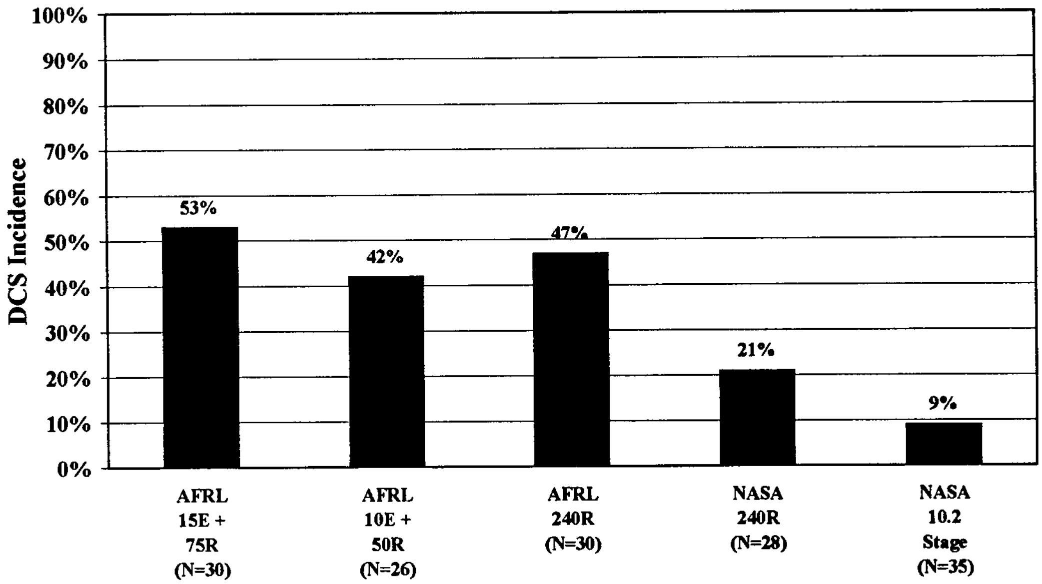

Figure 5. DCS Incidence during Exposure to 4.3 psia as a Function of Preoxygenation Condition: NASA vs Air Force Research Laboratory Results

with no difference in DCS risk (Fig 5), represents an enormous potential for cost/time savings during ISS construction.

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